KOPIO TN138

Neutrons and the vacuum upstream of the decay region

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Abstract

A specification for the vacuum upstream of the decay region is determined based on considerations of neutron interactions in the residual gas. Assuming an exponential pressure profile in the beam pipe and a pressure of 10^{-7} Torr in the decay region, the rate of photons due to interactions in the residual gas and the rate of neutron halo due to scattering in the residual gas should be negligible if the pressure at the upstream end of the upstream beam pipe is ~ 1 Torr or less.

1 Introduction

The factors that affect the specifications for the vacuum upstream (US) of the decay region are

1. The required pressure in the decay region,
2. the background rate of photons due to interactions of neutrons and charged particles in residual gas in the US region and
3. the increase in halo due to neutron scattering and neutron production in the residual gas.

A pressure of 10^{-7} Torr in the decay region produces negligible background from $nN \to \pi^0 X$ interactions in the residual gas [1] and sets the first factor. The other two factors are discussed in this note.

2 Photon rate

I used the FastMC [2] to estimate the rate of photons entering the decay region due to $nN \to \pi^0 X$ in the residual gas in the US region following the method used in TN047 [1].

The rate of photons per microbunch produced by $nN \to \pi^0 X$ reactions in the residual gas that exit the US beam pipe and enter the decay region is

$$N_n N_A \sigma \int_{z_1}^{z_2} dz f(z) \rho(z)$$

where

- N_n is the number of beam neutrons per microbunch,
- N_A is Avogadro's number,
- σ is the $nN \to \pi^0 X$ cross section,
- $f(z)$ is the fraction of times that a photon produced by $nN \to \pi^0 X$ at z enters the decay region, and
- $\rho(z)$ is the density of the gas in the US pipe as a function of z.

The number of protons incident upon the target per microbunch assuming a 5 second spill is

$$\frac{100 \times 10^{12}\ p}{\text{spill}} \times \frac{\text{spill}}{5\ s \times 25 \times 10^6 \text{ microbunch}/s} = \frac{100}{125} \times 10^6\ p/\text{microbunch} \approx 10^6\ p/\text{microbunch}\ .$$

From TN007 [3], the number of neutrons per beam proton per μsr is $3.06/1.22 \times 10^{-6}$ ($2.02/1.22 \times 10^{-6}$) at $38.5°$ ($46.5°$) for $E_n > 10$ MeV. For a 90×4 mrad^2 acceptance, this implies 903 (596) neutrons per microbunch before spoiler attenuation. I neglect the attenuation and degradation of the neutron beam by the spoiler and assume $N_n = 1000$.

As in TN047 [1], I assume that the entire neutron-nucleon cross-section σ above π^0 production threshold is due to $nN \to \pi^0 X$ and that $\sigma = 35$ mb $= 3.5 \times 10^{-26}$ cm^2.

The FastMC was used to estimate $f(z)$ by generating the reaction $nN \to \pi^0 X$ at $\vec{x} = (0, 0, z)$ with $z = 50, 100, ...950$ cm. The FastMC model for the $nN \to \pi^0 X$ reaction assumes phase space and baryon number conservation. The neutron beam spectrum is the same as in TN047 [1]. The downstream defining aperture of the US beam pipe is taken to have a half-width of 92.5 cm and a half-height of 5 cm as in TN137 [4]. Figure 1 shows the probability for a single photon $f(z)$ and both photons from the $nN \to \pi^0 X$ reaction to enter the decay region as a function of the z of the reaction point. The figure also shows the energy spectrum of the photons. Figure 2 shows the normalized energy spectra of the photons entering the decay region. The average photon energy decreases from $\sim$190 to $\sim$150 MeV as z increases from 50 cm to 950 cm and reflects the mild correlation between energy and photon angle induced by the boost from the neutron beam spectrum.

For the purpose of discussion, I assume that $\rho(z) = \rho_0 = 1.29 \times 10^{-3}\ g/\text{cm}^3 \times 1/760 = 1.70 \times 10^{-6}\ g/\text{cm}^3$ as the density of air [5] at 1 Torr. Taking $f(z) = 1$, the rate of single photon production from $nN \to \pi^0 X$ reactions in 1 Torr of air in a microbunch is

$$1000 \times 6.022 \times 10^{23}/g \times 3.5 \times 10^{-26}\ \text{cm}^2 \times 1.70 \times 10^{-6}\ g/\text{cm}^3 \times 1000\ \text{cm} = 0.0358$$

where I have assumed that the US region is 1000 cm long. (If the spoiler ends at 50 cm and the decay region begins at 997 cm [4], then the US region is 947 cm.) How does a rate of $\sim 0.04\gamma$/microbunch from $nN \to \pi^0 X$ compare with the rate of photons per microbunch from other sources?

Andrei Poblaguev simulated the target and collimation system using GEANT3. In his simulation the target and collimator are in vacuum, so the $nN \to \pi^0 X$ process in the residual gas does not occur. He separated the outgoing particles into "beam" and "halo". **This is not Andrei's standard definition of "beam" and "halo".** The "beam" particles are those with trajectories at the second collimator ($z = 331$ cm) that will enter the decay region. The "halo" particles are all others. For 10^9 incident protons on target, there are 2870 photons in the “beam” or $2.87 \times 10^{-6}\gamma/p$. For 10^{12} incident protons on target, there are 68616 photons in the “halo” or $0.0686 \times 10^{-6}\gamma/p$. In total, one expects $2.94 \times 10^{-6}\gamma/p$ dominated by photons in the beam envelope. Assuming 10^6 protons per microbunch, there should be 2.94 γ per microbunch in the “beam” and “halo” or about two orders of magnitude more than that expected for $nN \to \pi^0 X$ even without a reasonable vacuum or taking into account a realistic $f(z)$. This is not surprising since there is 7 cm of lead for the spoiler in the beam.

In Figure 4, two possible pressure profiles are convolved with $f(z)$ to estimate the rate of photons entering the decay region due to $nN \to \pi^0 X$ interactions. The pressure profiles assume exponential dependence on z and assume that the pressure at the entrance to the decay region ($z = 1000$ cm) is 10^{-7}. (In reality the minimum pressure will be at the port of the pumping station that is now planned to be between the D3 magnet and the decay region.) The pressure at the upstream end of the upstream pipe ($z = 50$ cm) is assumed to be either atmospheric pressure (760 Torr) or 1 Torr. When the US end of the pipe is at atmospheric pressure (1 Torr), the rate of photons per microbunch is 1.2×10^{-3} (2.3×10^{-6}).

One concern is that the photon energy spectra from $nN \to \pi^0 X$ and the “beam” and “halo” differ. Figure 3 shows that photons from $nN \to \pi^0 X$ are indeed stiffer than those in the “beam” and “halo”; however, for any threshold, the relative flux is only about ten times larger for $nN \to \pi^0 X$ than the “beam” and “halo” (lower plot in Figure 3).

These calculations assume that the interactions of particles in the beam other than neutrons with the residual gas do not contribute to the rate of photons entering the decay region. This assumption is probably reasonable for the region downstream of the D1 and D2 magnets when all the charged particles have been swept from the beam. In the upstream region of the pipe, there should be a copious flux of charged particles that could interact with the residual gas. From Figures 8 and 10 of Ref. [7], the charged particle flux from the target before the spoiler is dominated by pions, neutrons and protons; the charged pion flux is at most 10 times the neutron flux and the proton flux is comparable to the neutron flux.

Assuming a factor of ten increase due to possible photon production from charged pion and proton interactions in the residual gas and an effective factor of ten due to the stiffer spectrum, the expected rate of photons per microbunch entering the decay region would increase to $2.3 \times 10^{-6} \times 10^2 \approx 2 \times 10^{-4}$ assuming the US end of the pipe is at ~ 1 Torr. This is well below the expected rate of $\sim 3\gamma$/microbunch due to the collimation system.

3 Increase in halo

Neutron scattering in the residual gas in the US region could increase the neutron halo. To estimate the size of this effect I used GEANT3 with the GCALOR hadronic interaction package with the modifications to neutron interactions as described in Ref. [6]. I generated 100000 neutrons with $\vec{p} = (0, 0, p_z)$ at each value of $p_z = 200, 300, 400..., 2500$ MeV/c at $\vec{x} = (0, 0, -0.5)$ cm in a 1 cm sphere of air at STP centered on the origin. I then counted all neutrons that resulted from scatters and all neutrons that projected to $|y(z = 1000 \text{ cm})| > 5$ cm as an estimate of the halo. All neutrons that were produced in interactions were counted so there could be multiple ’scattered’ neutrons per incident neutron. In addition note that I neglect the possible reduction in the halo due to the collimation system.

Figure 5 shows the results. The rate of scattered and halo neutrons per incident neutron is $(2.63 \pm 0.10) \times 10^{-5}$ and $(2.49 \times 0.10) \times 10^{-5}$, respectively, assuming it is independent of neutron momentum. This is amazingly close to the calculated rate assuming a cross section of 35 mb:

$$\text{scatter}/n = N_A{\cdot}\sigma{\cdot}\rho{\cdot}L = 6.022{\times}10^{23}{\cdot}3.5{\times}10^{-26}\ \text{cm}^2{\cdot}1.29{\times}10^{-3}\ g/\text{cm}^3{\cdot}1\ \text{cm} = 2.72{\times}10^{-5}\ .$$

Using these results and the pressure profiles in Figure 4, the scattered neutron rate as a function of the pressure at the US end of the US region is shown in Figure 6. The pressure at the US end of the US region needs to be below $\sim$5 Torr to keep the neutron halo from this source below 10^{-5} or less than 10% of the nominal neutron halo due to the collimation system of $\sim 10^{-4}$.

I performed similar studies with incident protons and charged pions on the 1 cm sphere of air. Using the same definitions and assumptions as above, the neutron halo rates per incident particle are $(1.42 \pm 0.31) \times 10^{-5}/p$, $(1.33 \pm 0.36) \times 10^{-5}/\pi^+$ and $(1.89 \pm 0.32) \times 10^{-5}/\pi^-$. It is difficult to assess the effect of neutron halo production by these charged particles because the flux of charged particles after the spoiler is unknown and the effect of the magnetic field on the flux as a function of z is not precisely known. Conservatively assuming that the relative fluxes of n, p and $\pi^\pm$ are the same after the spoiler as before the spoiler, the magnetic field has no effect on the charged particle flux, the pion flux is 10 times the neutron flux and the proton flux is the same as the neutron flux, the rate of neutron halo would increase by a factor of

$$\frac{1 \times 2.49 + 1 \times 1.42 + 10 \times 1.33 + 10 \times 1.89}{1 \times 2.49} = 14.5$$

times the rate from neutrons alone. The expected neutron halo rate under these assumptions is shown in Figure 6 and the pressure at the US end of the US region would need to be below $\sim$0.3 Torr to keep the neutron halo below 10^{-5}.

4 Conclusion

Considerations of the increase in the rate of halo neutrons dominate the determination of the maximum pressure in the upstream beam pipe. The rate of photons due to interactions in the residual gas and the rate of neutron halo due to scattering in the residual gas should be under control if the pressure at the upstream end of the upstream beam pipe is ~ 1 Torr or less, assuming an exponential pressure profile in the beam pipe and a pressure of 10^{-7} Torr in the decay region.

5 Acknowledgements

I thank Dana Beavis for suggesting (demanding?) this study and for useful comments and suggestions. Andrei Poblaguev pointed out the possible effect of the residual gas on the neutron halo and ran lots of useful Monte Carlo.

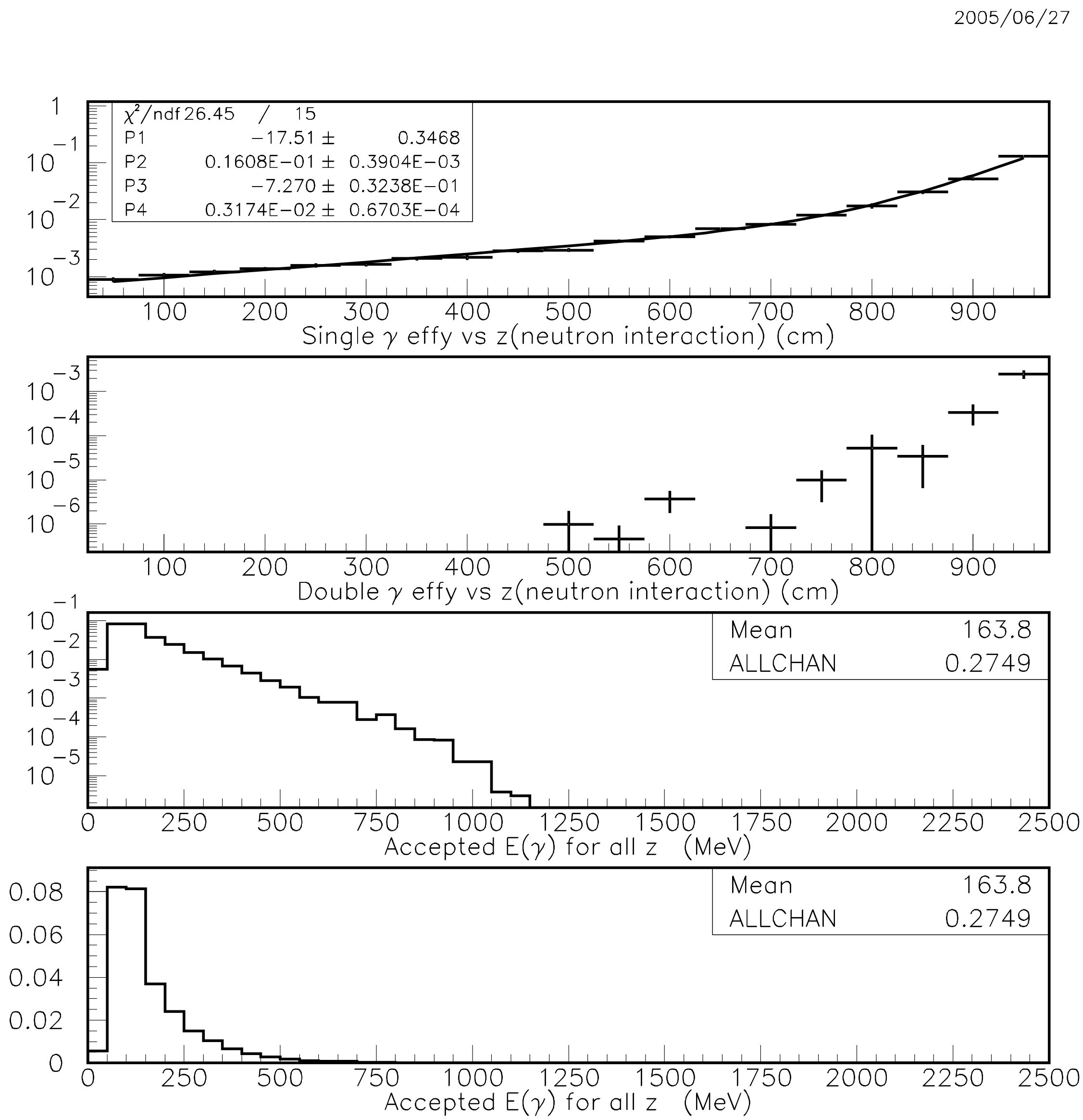

Figure 1: Top: The efficiency for a single photon from the $nN \to \pi^0 X$ reaction to enter the decay region as a function of the z of the reaction point. The fit is $e^{p_1+p_2 z} + e^{p_3+p_4 z}$. Next: The efficiency for both photons from the $nN \to \pi^0 X$ reaction to enter the decay region as a function of the z of the reaction point. Next: The energy spectrum of photons that enter the decay region summed over all generated z positions on a log scale. Bottom: Same, but with a linear scale.

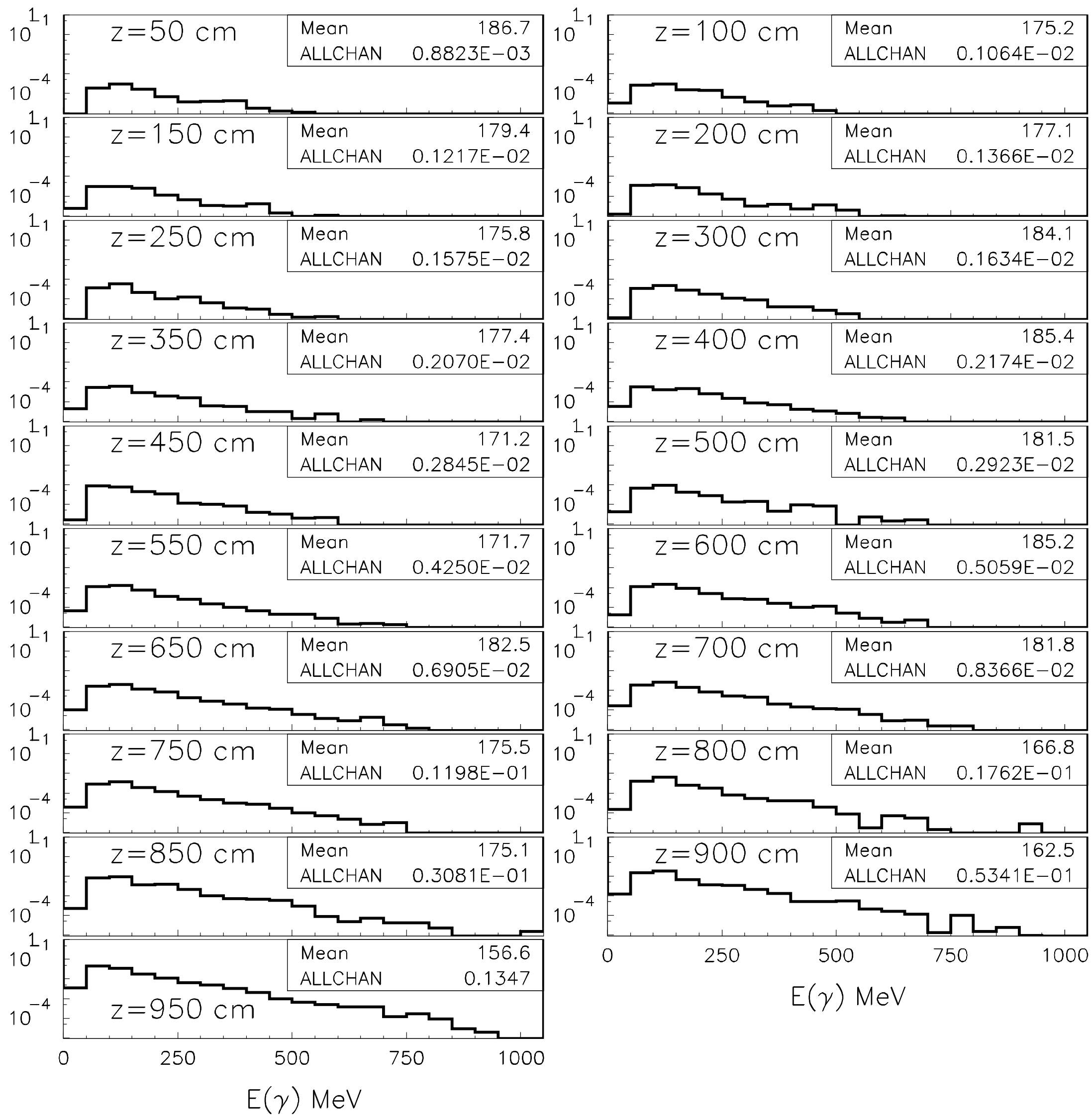

Figure 2: The energy of the photons from the $nN \to \pi^0 X$ reaction that enter the decay region as a function of the z of the reaction point. The histograms are normalized to give the probability ("ALLCHAN") that a photon from the $nN \to \pi^0 X$ reaction to enter the decay region. The vertical scale on each plot ranges from 10^{-5} to 1 for comparison.

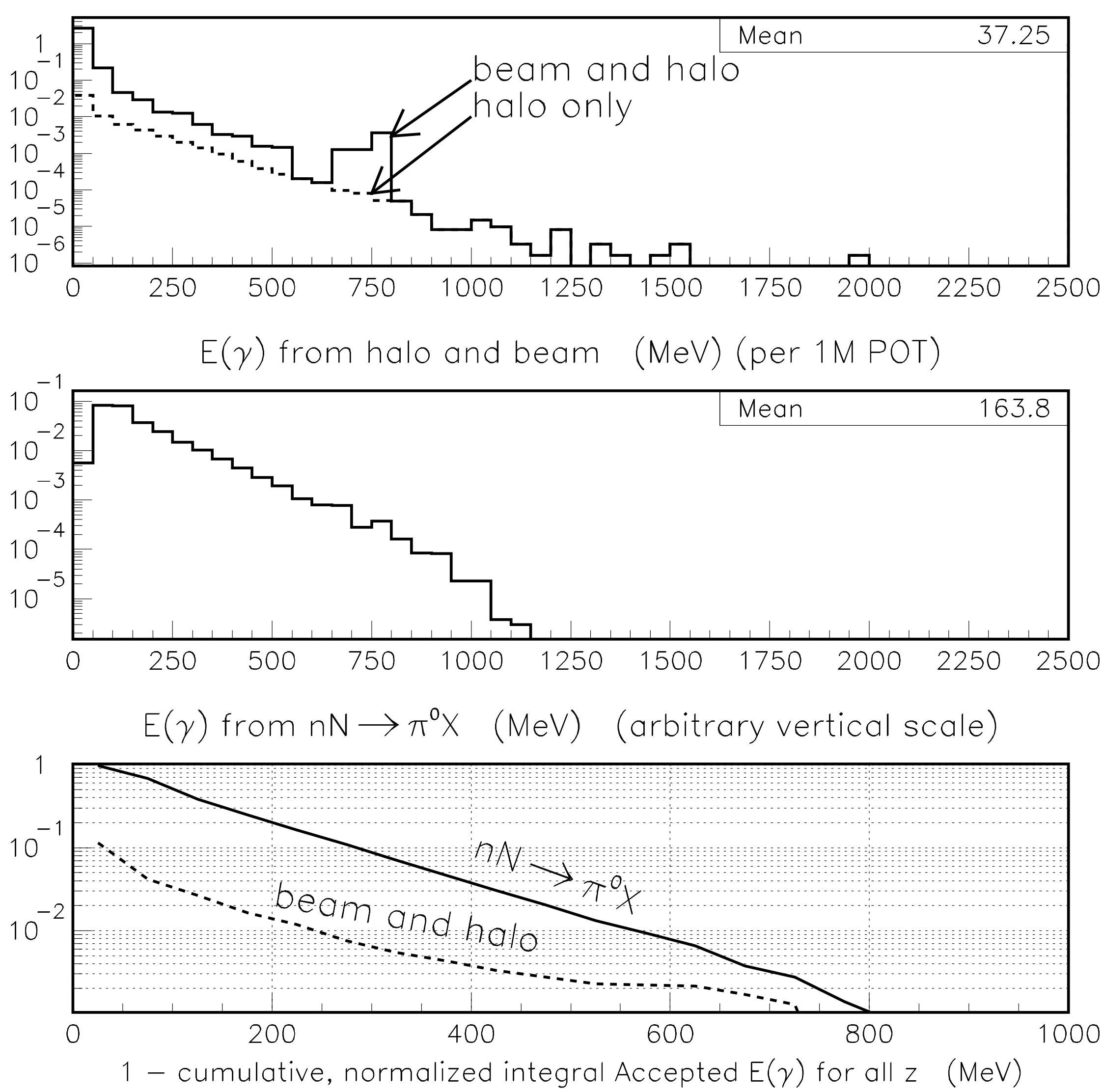

Figure 3: Top: Energy spectrum of photons in the "beam" and "halo" (see text for details). Middle: The energy of the photons from the $nN \to \pi^0 X$ reaction that enter the decay region. Bottom: $1 - \int_0^E dE' f(E') / \int_0^\infty dE' f(E')$ where $f(E)$ is the energy spectrum.

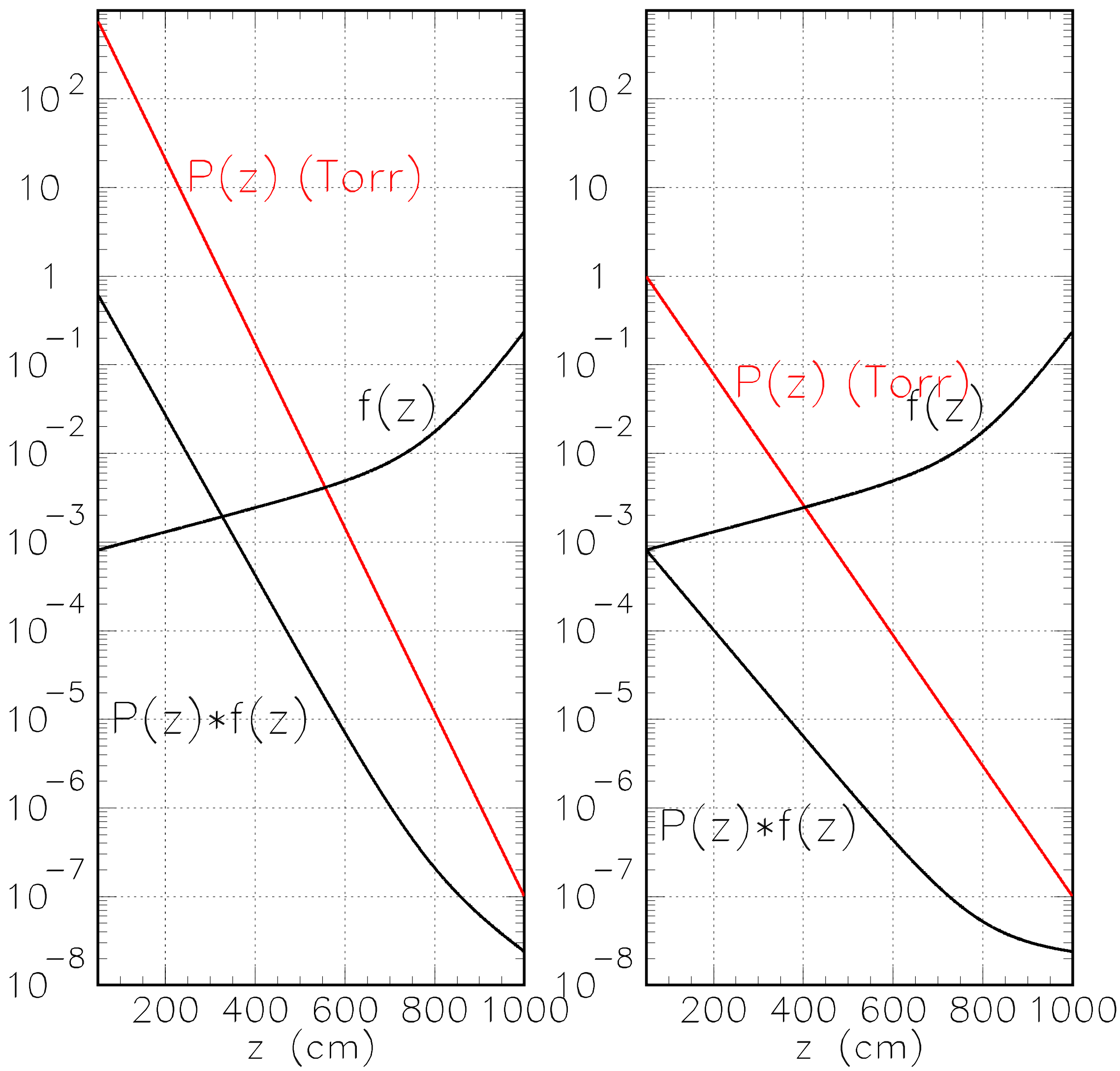

Figure 4: Assumed pressure profile $P(z)$ in the US pipe as a function of z (red), the fraction of photons $f(z)$ from $nN \rightarrow \pi^0 X$ that enter the decay and the product for two pressure profiles. The profile on the left (right) assumes a maximum pressure of 760 Torr (1 Torr) at the upstream end of the upstream beam pipe.

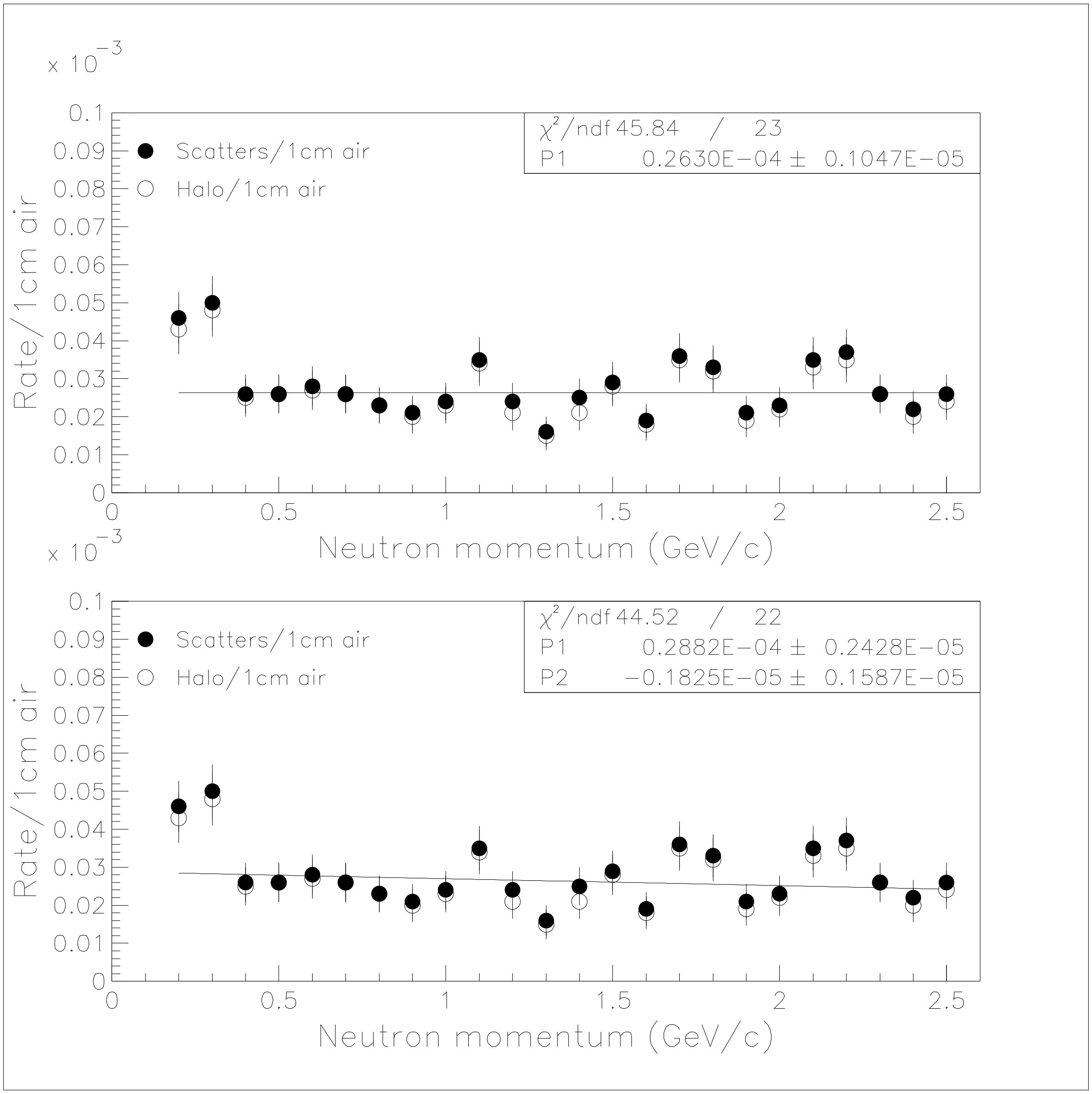

Figure 5: The rate of scattered neutrons per incident neutron as a function of neutron momentum as determined by the GEANT3/GCALOR simulation. The upper (lower) plot shows the results of a fit with 0th- (1st-) order polynomial. The same data are shown in both plots.

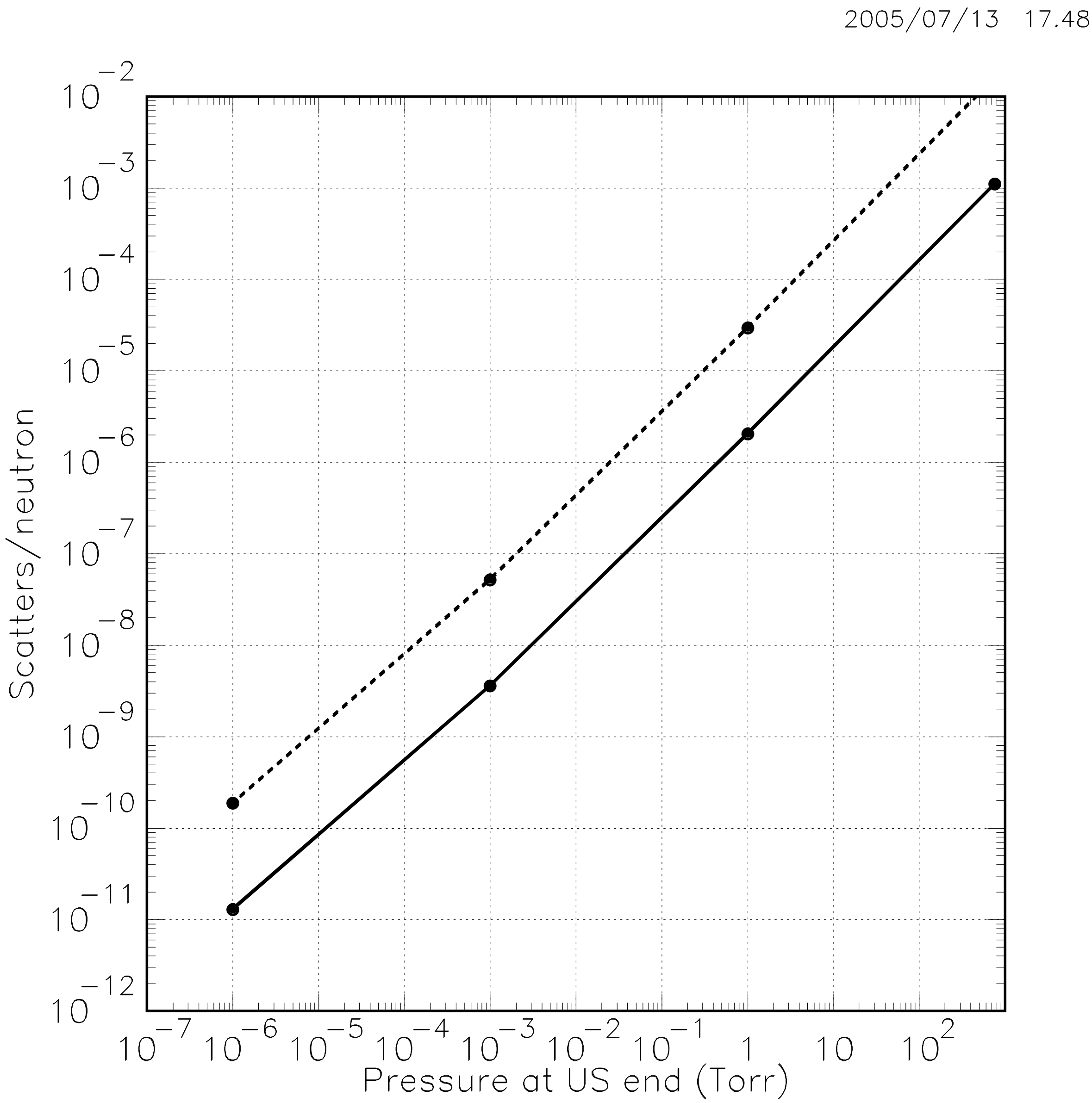

Figure 6: The solid line is the estimated rate of scattered neutrons per incident neutron as a function of the pressure at the upstream end of the upstream region assuming exponential pressure profiles as shown in Figure 4. The dashed line is the estimated rate of halo neutrons assuming neutron, proton and charged pion fluxes as described in the text.

References

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[4] D.E. Jaffe, *Background from K_L decays upstream of the decay region*, KOPIO TN137, 16 June 05.

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